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Environmental Health Center
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APPLICATION OF BIOLOGICAL METHODS IN THE TREATMENT OF RADIOACTIVE WASTES*

The objective of this paper is to review some general aspects of the radioactive waste disposal problems and point out the possibilities of the use of biological methods in the treatment of such wastes. It will be impossible in the present paper to go into details as to the fundamental principles of radiation or all phases of radioactive waste problems. There have been many papers recently which discuss the elements of radioactivity. Briefly, radioactive substances are unstable and are continuously disintegrating through the emission of alpha or beta particles and sometimes electromagnetic (gamma) rays. These are all ionizing radiations and are, consequently, destructive to body tissues depending upon intensity and duration.

The radioactive waste disposal problem has grown by leaps and bounds along with the rapid development in the use of radiation equipment, Atomic Energy Commission reactors, and radioisotopes for scientific uses. It is interesting to observe that in the Federation of Sewage and Industrial Wastes Associations' Review of Literature for the year 1951 (13), there are references to 94 articles dealing with radioactive wastes in some manner.

(*) Presented at the Central States Sewage and Industrial Wastes Associations Meeting, Madison, Wisconsin, June 26, 1952

There are liquid, solid and gaseous radioactive wastes. We are primarily concerned with liquid waste and will confine our attention in this paper largely to them. The principal producers are the Atomic Energy Commission installations, particularly reactors and processes leading to the production of radioactive isotopes, although hospitals, research laboratories and industrial users must be included as producers of radioactive waste.

Classification of Waste

The liquid wastes may be classified on the basis of the type of radioactivity emitted, the energy level, the rate of natural decay or half-life, and the biological toxicity or half-life. All of these factors are important in considering methods of waste treatment. The radioactive density of a waste may vary tremendously from levels slightly above the natural background of water to very high values. Generally, only relatively . low level radioactive wastes, regardless of type, can be considered for biological treatment. The half-life of the isotope, which may vary from millions of years to seconds, also affects the treatment to be given the waste. Materials containing only short half-life isotopes of a few days or less can be stored to allow the activity to decay for about 10 half-lives and then discharged into a sewerage system. The hazard from such disposal will be relatively low provided the residual radioactive density of the liquid or sludge is not dangerous to personnel.

Low level waste containing long half-life isotopes, such as plutonium, may be successfully treated by industrial water and sewage treatment processes including biological processes to levels permissible in drinking water.

Methods of Treatment

The specific method of treatment selected for a waste will depend upon the type, toxicity, and radioactive concentration of the waste and may include physical, chemical, biological, or a combination of these treatment processes. The common physical methods of disposal include storage, evaporation and storage of the solids, ground and sea burial of solids and liquids and, last but not least, disposal by dilution. The evaporation and storage of concentrated waste is generally the method of choice for high level wastes because the volume to be stored is reduced and the condensate is relatively free of radioactivity. It should be noted here that the radioactivity is simply separated from the liquid and retained in a small residual volume which must be stored. If the materials have a very long half-life the storage must be for a very long time. Thus plutonium waste would require storage for 250,000 years before the activity decayed through 10 half-lives.

Figure 1 shows a system of evaporation which has been developed by McCullough and his associates [4]. This is very effective and permits the discharge of the vapor condensate to the neighboring stream with practically no contamination therein. However, this method of disposal

is very costly. The cost of disposal by evaporation in Atomic Energy Commission installations has been stated to be 8 cents to 12 cents per gallon. Eight cents per gallon or $80,000 per million gallons is a tremendous cost compared to ordinary sewage treatment.

Burial in the ground has been proposed for some kinds of radioactive waste. The problem of ground burial is receiving the attention of the Subcommittee on Waste Disposal and Decontamination, National Radiation Protection Committee, National Bureau of Standards. A Bureau of Standards memorandum on this method for guidance of those charged with responsibility for the safe disposal of radioactive isotopes will soon be published. Disposal at sea is another common method which is being practiced at the present time by our Armed Services and the National Institutes of Health. The National Bureau of Standards Subcommittee is currently preparing a manual for guidance on sea disposal. The Atomic Energy Commission has also considered the return of waste and used isotopes to the Commission in case of hazardous materials in quantities which cannot be easily disposed of by isotope users.

The discharge of isotopes into sewers is of immediate interest to members of the Federation of Sewage and Industrial Wastes Associations. So far, the Waste Disposal Subcommittee, mentioned above, has considered only the disposal of I^{132} and P^{32} as permissible. The levels and quantities which may be discharged into sewers under prescribed conditions from hospitals are given in Handbook No. 49 of the National Bureau of Standards (5).

The handbook recommends discharge of institutional wastes in a manner that will not permit a transient concentration higher than 100 microcuries per liter. One would have to drink a whole liter of such sewage to obtain a permissible tracer dose of P^{32} and I^{131}. It was presumed that the consumption of such a quantity of sewage would be a rare accident, and, consequently, the ingestion of a tracer dose could be tolerated. This concentration would exist only in the sewage leaving the institution and would be greatly diluted in the trunk sewer and the interceptor before reaching the treatment plant or final discharge point into a stream. It would be interesting to estimate the ultimate equilibrium concentrations of these isotopes that may be expected if the daily isotopic wastes are diluted and mixed with the quantity of water used daily in the city. It is realized that the distribution of hospital facilities and sewage collection facilities would not be such that the waste could be expected to be uniformly diluted in the entire city flow. However, the theoretical values obtained in this calculation (see Table) are instructive in showing the relative magnitude of the radioactivity to be expected from this source. It will be noted that the radioactivity from these isotopes diluted in this manner varies from 0.25 to 0.6 x 10^{-3} microcuries per liter and even if all the I^{131} and P^{32} waste in any of these cities was diluted into a system carrying only two per cent of the daily water supply, the expected radioactive concentration would still be less than the permissible level in drinking water for continuous use.

It may be remembered that 1 microcurie is 2.23 million atoms disintegrating per minute. Thus, 0.25×10^{-6} μc is only 55 atoms disintegrating per minute. Consequently, quantities of radioactive elements which may be easily detected by radioactive assay are trace amounts which could not be detected by ordinary chemical analysis. To understand the significance of the concentration that may be expected in interceptors, it may be interesting to compare these values with the standards that have been suggested by the Atomic Energy Commission for drinking water under various conditions.

Table 2 shows the permissible levels of alpha and beta activity in drinking waters as proposed by several authorities. It will be noted that these values are very much higher than the values to be expected after complete dilution in sewage of metropolitan areas in the United States (Table 1).

The radioactivity in microcuries per liter for various natural springs is shown in Table 3. For comparison, the permissible levels in drinking water for continuous and emergency use and the theoretical concentration from the discharge of I^{131} and P^{32} for Los Angeles sewage are also included. It will be noted that the Los Angeles sewage radioactivity concentration which is representative of what may be expected in any metropolitan sewage is very much lower than the value for P^{32} in water for continuous use. The background levels for normal surface and ground waters of the United States are also included in this table. A careful comparison of

the data in Table 1 with the permissible radioactivity in drinking waters suggested by the Atomic Energy Commission indicates that there need be no fear of the contamination of our surface waters from the I^{131} and P^{32} wastes which are presently discharged into sewers by medical users.

Chemical Methods

Chemical methods for the treatment of radioactive waste include: (a) deposition on metal or absorption on activated carbon, clays or other adsorbants, (b) ion exchange processes, and (c) coagulation and/or carrier precipitation followed by filtration.

Many papers on the use of chemical procedures have been published. The use of coagulation-carrier precipitation in a waste water treatment plant similar to that used in ordinary water purification practice has been applied at Los Alamos [7,10].

Biological Methods

The biological treatment which would be applicable to relatively low level radioactive waste includes activated sludge, trickling filter treatment and absorption by algae and other plankton forms. To date there has been no reported applications of the latter method, although algae and plankton serve as concentrators of activity in streams even when they are slightly polluted with radioactivity.

The application of biological methods to the treatment of radioactive waste was first studied at Los Alamos [6,8,9]. It was found that activated

sludge and trickling filter processes could be successfully used in the removal of plutonium in low concentrations from the waste waters. Studies at Los Alamos also indicated that biological processes were of special importance and were the only practical methods available for treating waste relatively high in organic acids which sequester the coagulants used in chemical treatment. It was also shown by this laboratory that an activated sludge capable of removal of radioactive materials could be produced from ordinary nutrients such as glucose and flour [12]. On the basis of a continuation of experiments at Los Alamos a plant for treating an unusual waste containing considerable quantities of citrate (sometimes as high as 20,000 p.p.m.) has been built and operated.

Preliminary bottle experiments have been conducted at this Center on the removal of P^{32} and I^{131} by activated sludge. A single experiment on the treatment of mixed fission products by activated sludge has also been completed.

GENERAL EXPERIMENTAL PROCEDURE

One liter graduated cylinders having a bottle type neck were used as aerators by submerging a one-inch ceramic diffuser ball at the end of a rubber tube to the bottom of a cylinder containing one liter of mixed liquor under aeration. Compressed air was admitted to each cylinder at a liberal rate which neither caused settling of sludge nor troublesome foam.

A six-day "Cold Run", i.e., without radioactivity, preceded the phosphorous studies for the purpose of making adjustments in aerator solids and testing the technique of operation. The mixed liquor originally placed in the aerators consisted of 200 ml. of activated sludge and 800 ml. of feed. The activated sludge had been acclimated for several months on the type of food to be used.

Feeding Schedule

From Monday through Friday of each week, the aerators were fed twice daily at 8:30 to 9:00 A.M. and again at 4:00 to 4:30 P.M. After sampling mixed liquor, the air diffuser was removed to allow the sludge to settle for 30 minutes. Seven to eight hundred milliliters of the cloudy supernatant were then decanted and immediately replenished to the original one liter volume with sewage or tap water containing the required amount of nutrients and minerals.

Tests

A 50 to 100 ml. sample of mixed liquor was withdrawn with a pipette for purposes of testing the suspended solids and sludge radioactivity. The sample of mixed liquor withdrawn for test purposes was usually sufficient to maintain a constant aerator solids content. The volume of sludge after settling for 30 minutes was recorded and used to determine sludge volume index (S.V.I.) and control operation.

Samples of supernatant after 30 minutes settling were tested periodically for pH, B.O.D. (five day) and suspended solids as indices of operation. Duplicate 10 ml. volumes of supernatant were evaporated in aluminum dishes at low heat and assayed for radioactivity by counting on the second shelf of a Geiger-Müller end-window counter. The efficiency of the counter was determined to be 6.53 per cent of the disintegrations based on a calibration of P^{32} standards counted in an internal proportional counter. Correction factors for geometry, self-absorption, backscatter and extended source were applied to the internal proportional counter data.

The counting data of morning samples were determined within a matter of an hour or two so no correction for decay was made. On the other hand, the afternoon samples were counted 24 hours after sampling on week days and the Friday afternoon samples were counted on Monday afternoon so appropriate decay factors were applied.

The radioactivity of the sludge solids was determined by centrifuging 50 ml. of mixed liquor, transferring the centrifuged cake to aluminum counting dishes with distilled water, evaporating slowly to dryness and counting. The Geiger-Müller end-window counting rate was corrected for self-absorption and coincidence losses.

Feed

Two of the four sludges in an experimental run were fed 700 to 800 ml. of domestic sewage twice daily, five days per week for two weeks. The other two sludges were fed synthetic sewage consisting of a mixture

of flour and sugar in 700 to 800 ml. of tap water twice daily five days per week for two to four weeks. The synthetic sewage feed was usually fortified with stable phosphorous, P^{31}, (trisodium phosphate) to maintain control of the process. All sludges received about 0.5 uc of radioactive element at each feeding. Radioactive phosphorous (P^{32}) was added as a phosphate salt and radioactive iodine (I^{131}) was added as potassium iodide.

UPTAKE OF P^{32} BY ACTIVATED SLUDGE

In designing an experiment to determine the uptake of P^{32} by activated sludge, it was learned from previous studies [12] that phosphorous additions to common foods were essential to activated sludge process control. White flour contains from 0.09 to 0.10 per cent of total phosphorous and it might be assumed that this would provide ample available phosphorous for the metabolic requirements of the sludge. However, the experiments [12] indicated that about 3.0 p.p.m. or more of supplemental phosphorous as phosphates were required with the common food being used to produce sludges with satisfactory settling indices. In our experiments the lack of sufficient available phosphorous to produce a sludge with a satisfactory settling index was considered the criteria for phosphorous deficiency. The stable phosphorous content of domestic sewage is fairly constant and has been reported [14] to average from about 1.7 to 4.0 p.p.m. as P. Usually domestic sewage provides sufficient available phosphorous for process control. Since microorganisms do not differentiate between isotopes of the same chemical element in identical

chemical form, the uptake of radioactive phosphorous will depend upon the abundance and availability of the total phosphorous. In view of this fact, the addition of 10 milligrams of stable (non-radioactive) phosphorous per microcurie of radioactive phosphorous waste had been recommended (1) as a method of waste disposal to sewers.

In these experiments the uptake of radioactive phosphorous was studied in four aerators. Of these aerators A and B were fed flour and glucose, and were also given 1 and 3 p.p.m. of stable phosphorous, respectively. Aerators C and D were fed settled sewage. Aerator C received no additional supplemental stable phosphorous, but aerator D received 3 p.p.m. of stable phosphorous in addition to the sewage. The stable phosphorous (P^{31}) was added as a stock solution of trisodium phosphate. The aerators were fed every morning and afternoon immediately following the removal of 700 to 800 ml. of settled supernatant from the 1 liter aerators. The experiment was continued for two weeks with no feeding over the week-end. The operating data on the activated sludges and the results on the removal of P^{32} are summarized in Table 4.

An inspection of the operating data indicates that:

(1) The aerators were loaded with 33 to 35 pounds of B.O.D. per day per 1,000 cubic feet of aerator capacity. However, the B.O.D. load per unit of aerator solids was least in the sewage fed sludges C and D and most in sludge A.

(2) The supernatant suspended solids are relatively high for normal plant operation on continuous feeding. However, laboratory batch feeding twice daily with excess air usually produces more turbid effluents. Somewhat better removal of P^{32} associated with these solids may be expected from large scale plant operation.

(3) The radioactive phosphorous, P^{32}, was added in an amount equal to approximately 0.5 uc per feed or an average of 1,200 disintegrations per minute per ml. This added activity resulted in the uptake of P^{32} by the activated sludge mixed liquor to a concentration roughly three times the feed in sludges B, C and D. In sludge A, fed synthetic sewage with only 1 p.p.m. stable phosphorous, the uptake of P^{32} by the sludge was much greater and accumulated in the mixed liquor to a concentration equal to six to seven times the concentration in the feed.

(4) The overall removal of P^{32} by the activated sludge was somewhat erratic from day to day. In sludge A, fed synthetic sewage with a minimum of phosphate, the removal of P^{32} varied from 52 to 88 or an average of 78 per cent of the feed. In sludge B, fed synthetic sewage with 3 p.p.m. of stable phosphate-phosphorous,

the overall removal varied from 12 to 77 or an average of only 43 per cent. In the sewage fed sludges the P^{32} removal varied from less than zero to 63 or an average of 35 to 38 per cent.

Fluctuations in the Uptake of P^{32}

The uptake of radioactive phosphorous during each feeding by the activated sludges fed on flour-dextrose is presented in Figure 2. The raw counting data on small samples were converted to disintegrations per minute (dpm) in the 700 to 800 ml. of supernatant withdrawn before each feeding. Since the counting was made following the decanting of supernatant, the radioactivity of feed and supernatant was corrected for decay to the time of decanting. The figure shows the amount of P^{32} added at each feeding and the total activity found in the supernatant. The amount of P^{32} appearing in the supernatant of the sludge fed a deficiency (1 p.p.m.) of stable phosphorous required for good process control was usually much less than half the amount of P^{32} in the supernatant from the sludge fed 3 p.p.m. stable phosphorous. The effect of no feeding over the week-end, particularly with a deficiency of phosphorous in the feed, is shown on the seventh and fourteenth day of the experiment. The Monday morning supernatants contained three times as much radioactive phosphorous as the Friday afternoon samples. This deterioration of the sludge probably would not occur in a continuously fed system. A similar plot of the supernatant results from sludges fed sewage with or without phosphate

fortification presented a scatter diagram of wide fluctuations. During the second week of operation, when it appeared that equilibrium conditions had been reached, the phosphate fortified sewage sludge passed slightly more P^{32}.

The Distribution of P^{32} in Activated Sludge

The distribution of P^{32} in activated sludge was determined weekly or biweekly. In preparing a balance at the end of a particular period the P^{32} in the feed, supernatants and sludges were all corrected for decay to the end of each period. Since P^{32} has a half-life of 14.3 days, the decay amounts to a loss of roughly five per cent of residual radioactivity in 24 hours. The results of the balances are presented in Table 5. Unfortunately, the radioactivity of the sludge wasted per day was assayed infrequently so that a significant error of this estimation may have occurred.

The Radioactive Density of Activated Sludge

When phosphate for activated sludge metabolism is deficient in the food, such as in sludge A, a much higher percentage of the radioactive phosphorous is assimilated and increases the radioactivity of the activated sludge. This is shown in the balance after two weeks in Table 5, Item 6, and, for purposes of emphasis, in Table 6 where the radioactive density of the sludges has been calculated per gram of dry sludge solids and per kilogram of three per cent settled sludge, Items 4 and 5, respectively. The table shows that the radioactivity of sludge A (fed a deficient supply of P^{31}) increased to 1.65 uc per gram of dry sludge solids in two weeks,

whereas sewage fed sludge accumulated a radioactivity density of only 0.6 uc per gram or less. Sludge B, fed flour-dextrose fortified with 3 p.p.m. P^{31}, accumulated a specific radioactivity in two weeks of 0.99 uc/gram.

UPTAKE OF I^{131} BY ACTIVATED SLUDGE IN THE PRESENCE OF STABLE IODINE

Studies on the uptake of radioactive iodine by activated sludge fed sewage or synthetic sewage containing stable iodine were performed in a two-week period similar to the radioactive phosphorous studies. Since it had been recommended (1) that radioactive iodine wastes might be discharged to sewers providing that one gram of potassium iodide was added to each millicurie of radioiodine, the sewage and synthetic sewage used in these studies were dosed with one to three parts per million of stable iodine (I^{127}) as the potassium salt and 0.5 uc I^{131}. A summary of the operating data is presented in Table 7. Sludges E and F were fed flour-dextrose fortified with 2.0 to 2.5 p.p.m. phosphorous and sludges G and H were fed sewage. Sludges E and G received one p.p.m. stable iodine while sludges F and H received 3 p.p.m. stable iodine. The concentration of aerator solids was maintained between 3,400 and 6,300 p.p.m. in sludges E and F, so that the B.O.D. loading of 44 pounds per day per 1,000 cubic feet was relatively low per unit of mixed liquor suspended solids. On the other hand, the B.O.D. loading of sewage fed

sludges G and F was comparable to the phosphate studies. The radioactive iodine added was 1,370 dpm per ml. of feed. The results show the radioactivity in the supernatants averaged 1230-1350 dpm per ml. showing a removal of I^{131} by activated sludge of 10 per cent or less. This value is within the experimental error of the radioactive iodine determination. However, it will be noted that the radioactive iodine found in mixed liquor was higher than the feed and indicates a low but significant accumulation of radioactive iodine in activated sludge fed nutrients containing 1-3 p.p.m. of stable iodine.

Experiments on the removal of I^{131} in the absence of stable iodine have not been completed. Pilot trickling filter studies conducted by Carter [2] indicated a removal of 85 per cent or more of carrier-free I^{131} in weak sewage when the dosage rate was 2 m.g.d. in a six foot filter and the level of I^{131} was 1,000 cpm per ml.

THE ABSORPTION OF RADIOACTIVITY FROM MIXED FISSION PRODUCT BY ACTIVATED SLUDGE

Two preliminary experiments on the absorptive capacity of activated sludge for three month old mixed fission product were made. An analysis of fission product of the age used from data by Tompkins and Cohn [15] is presented in Table 8. The experiments consisted of adding radioactive fission product to 500 ml. volumes of mixed liquor and aerating four hours or more. Periodically, 50 ml. samples were settled for 30 minutes. Ten ml. samples of the supernatant were collected, dried

and counted in an internal counter. The efficiency of counting was found to be 73 per cent of the true disintegration rate. A summary of the data is presented in Table 9. The results show that 40 to 50 per cent of the mixed fission product radioactivity was absorbed by activated sludge in one hour or less and that 75-77 per cent was absorbed in four hours of aeration.

DISCUSSION

The removal of radioactivity by activated sludge and the trickling filter may be affected by one or a combination of mechanisms. The more important possibilities appear to be:

(1) The aerobic microbiological destruction of complexing and sequestering agents associated with radioactive wastes. Other mechanisms of removal may then occur. This would seem to be the most important function of activated sludge for the removal or the preparation for the removal of radiocolloids in laboratory decontamination, laundry, and some process wastes.

(2) The physico-chemical adsorption of radioactive ions, colloids and suspended matter by the zoogleal mass in activated sludge or on filters. For this mechanism to be effective, it may be presumed that complexing agents and detergents must be destroyed or eliminated to a large degree as stated above.

(3) The utilization or synthesis of elements required in the growth and propagation of activated sludge or zoogleal masses on filters. Radioactive mineral nutrients will be utilized by activated sludge in proportion to the abundance of total like elements of similar availability. Thus, if the mineral nutrient, such as phosphorous, is deficient in the feed for activated sludge a high removal of radiophosphorous may be anticipated. However, in the presence of an abundant supply of non-radioactive available phosphate, a low percentage removal of radioactive phosphorous may be anticipated. In sludges A and B, the average radioactive phosphorous added was 960,000 dpm or 1.2×10^{-10} milligrams per feed as against 1 and 3 mg. of non-radioactive phosphate-phosphorous, respectively, and exclusive of an estimated 0.3 mg. of phosphorous in the wheat flour and minute amounts in the tap water. Thus, only traces of total phosphorous in the activated sludge feed were radioactive. However, an average of 78 per cent of the radioactive phosphorous was removed in sludge A because there was a deficiency of total phosphorous.

In the case of the iodine studies the radioactive iodine per feed amounts to 3×10^{-9} milligram as against the 1 or 3 mg. of non-radioactive iodine added. In this case the sludge has an affinity for total iodine

(which is not necessarily for metabolic purposes) and the preponderance of non-radioactive iodine results in low removal of radioactive iodine.

GENERAL SUMMARY AND CONCLUSION

In conclusion it may be stated that the maximum removal of radioactivity that may be expected by treatment in biological systems is about 95 per cent. Consequently, such systems can be used only on relatively low level wastes. It can also be generalized that:

(1) Biological treatment is not indicated for soluble isotopes that are not utilized or readily absorbed on biological floc as for example I^{131}.

(2) Biological processes are not satisfactory for the treatment and removal of isotopes of elements which are isotopically diluted by constituents in sewage. This is true even though the element is required for microbial propagation and normal metabolism of the sludge. The P^{32} experiments illustrate this.

(3) Biological treatment may be used for the removal of isotopes, such as plutonium, which have no isotopic dilution and which are easily absorbed by the zoogleal floc under proper conditions.

(4) Biological treatment may be used on waste containing, in addition to the radioactive isotope, organic materials which sequester or prevent chemical treatment for the

removal of the activity. In this case, the biological system is used simply to remove by oxidative assimilation the organic sequestering constituents. Following such removal the effluent may be chemically treated by flocculation, carrier-precipitation or other methods to remove the radioactivity.

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(*) Deceased

TABLE 1

Concentration of I^{131} and P^{32} to be Expected in Sewage of Six Large American Cities*

City	Average Dilution Water Needed per Day to Dilute Activity to 100 uc/liter-Assuming no Decay (Gallons)	Water Consumption of City per Day (Million Gallons)	Activity from I^{131} and P^{32} after Uniform Dilution by Volume of Water Used per Day (Microcuries per Liter)
New York	413	925	0.4×10^{-4}
St. Louis	95	160	0.6×10^{-4}
Chicago	363	900	0.4×10^{-4}
Los Angeles	94	150	0.6×10^{-4}
New Orleans	25	60	0.4×10^{-4}
San Francisco	25	100	0.25×10^{-4}

(*) Based on the quantities of these isotopes shipped to the cities listed by the Atomic Energy Commission during the first six months of 1950, as shown in reference 11.

TABLE 2

Proposed Levels of Radioactivity in Drinking Water

(microcuries per liter)

Time Water is to be Consumed	Maximum Permissible[a] Level		Emergency Low Risk[c] Level		Emergency Permissible[b] Limit	
	Alpha	Beta	Alpha	Beta	Alpha	Beta
10 Days			0.2	3.5	5	90
30 Days			0.07	1.1	1.7	30
Continuous Use						
Iodine^{131}		0.3				
Phosphorous^{32}		0.2				
Strontium^{89}		0.2				
Strontium^{90}		8×10^{-4}				
Radium^{226}	4×10^{-5}	-				
Plutonium^{239}	1×10^{-3}	-	2×10^{-2}*			
Unknown Sources	1×10^{-4}	1×10^{-4}				
Fission Product				4×10^{-3}*		

(a) Morgan, K. Z., "Quantitative Limits of Permissible Exposure of Personnel", Florida Eng. and Ind. Expt. Station Bull. Series No. 48, p.37 (Nov.1951)

(b) Emergency acceptable risk. Atomic Energy Commission, Ninth Semi-annual Report, p.19 (1951)

(c) Application of a safety factor of 25 to Atomic Energy Commission permissible limits, Handbook of Atomic Weapons for Medical Officers, NavMed - T - 1330, U. S. Government Printing Office (1951)

(*) Safe Levels, "The Effects of Atomic Weapons", U. S. Department of Defense and U. S. Atomic Energy Commission, p.396 (September 1950), U. S. Government Printing Office

TABLE 3

Radioactivity of Some Spring Waters Compared to Emergency Permissible and Background Levels and the Theoretical Value in Los Angeles Sewage

Location	Source	Radioactivity Microcuries per Liter	Reference
Saratoga Springs	Hathorn No. 1	1.42×10^{-4}	a
Yellowstone Park	Monmouth Hot Springs	14.4×10^{-4}	a
Hot Springs, Ark.	Imperial Spring	90.3×10^{-4}	a
Manitou, Colorado	Shashone Spring	33.8×10^{-4}	a
Italy - Ischia	Old Roman Spring	1525×10^{-4}	a
U. S. Normal Surface Waters	15 Samples	$.0036$ to $.0341 \times 10^{-4}$	a
U. S. Normal Ground Waters	25 Samples	$.0058$ to $.039 \times 10^{-4}$	a
Los Angeles Sewage	(Theoretical)	0.6×10^{-4}	b
Emergency Drinking Water	(Alpha, acceptable for 10 days)	$50,000 \times 10^{-4}$	c
Emergency Drinking Water	(Alpha, acceptable for 30 days)	$17,000 \times 10^{-4}$	c
Continuous use of Drinking Water	Unknown	1.0×10^{-4}	c
Continuous use of Drinking Water	Phosphorous^{32}	$2,000 \times 10^{-4}$	c

(a) According to Love(3)
(b) See Table 1
(c) See Table 2

TABLE 4

Operating Data on the Uptake of P^{32} by Activated Sludge

Activated Sludge	A	B	C	D
Feed (twice per day)	Syn. Sew.(a)	Syn. Sew.(a)	Sewage(b)	Sewage(b)
B.O.D. load, lbs/D/1000 cf.	35	35	33	33
P^{31} added, p.p.m.	1	3	0	3
P^{32} added, dpm/ml.	1200	1200	1200	1200
Aerator Susp. solids, p.p.m.	2100-2500	1800-2200	2500-3100	2800-3100
Settleability range, S.V.I.	28-80	19-47	31-43	36-39
P^{32} in Mixed Liquor, dpm/ml.	8600	4240	3880	3670
Supernatant				
Susp. Solids, p.p.m.	89	113	25	13
B.O.D. p.p.m.	15	20	9.5	9.0
P^{32}, dpm/ml.	270	705	744	800
pH	6.9-7.5	6.9-7.6	6.8-7.8	6.8-7.8
Removal of P^{32}				
Range, per cent	52-88	12-77	8-63	-11-56
Average*, per cent	78	43	38	35

(a) Feed of 0.3 gram wheat flour and 0.1 gram dextrose in 800 ml. tap water - B.O.D. of 336 p.p.m.
(b) Feed of 800 ml. domestic sewage - Estimated B.O.D. of 320 p.p.m.
(*) Weighted average for a two-week period.

TABLE 5

The Distribution of Radioactive Phosphorous in Activated Sludge

Activated Sludge	A	B	C	D
Feed	Syn. Sew.	Syn. Sew.	Sewage	Sewage
P^{31} in Feed, p.p.m.	1	3	0	3
	P^{32} Balance after One Week (Millions of dpm)			
Item				
1. Added in Feed, less decay	6.96	6.96	6.96	6.96
2. In Supernatant	1.13	2.25	3.01	2.96
3. In mixed liquor at end	4.87	3.41	2.10	2.54
4. Calc. to be in Waste Sludge 1-(2+3)	0.91	1.3	1.85	1.46
5. Found in Wasted Sludge	1.37	0.57	0.35	0.43
6. Unaccounted for (4-5)	-0.46	0.73	1.5	1.03
	P^{32} Balance After Two Weeks (Millions of dpm)			
1. Added in feed, less decay	9.45	9.45	9.45	9.45
2. In Mixed Liquor at Start	3.30	2.31	1.42	1.72
3. In Supernatant	2.41	6.37	6.23	6.65
4. Mixed Liquor at end	8.4	3.96	3.35	3.00
5. Calc. to be in Waste Sludge (1+2)-(3+4)	1.94	1.43	1.29	1.52
6. Found in Wasted Sludge	2.04	0.91	0.67	0.68
7. Unaccounted for (5-6)	-0.10	0.52	0.62	0.84

TABLE 6

Radioactive Density of Activated Sludge

Activated Sludge	A	B	C	D
Feed	Syn. Sew.	Syn. Sew.	Sewage	Sewage
P^{31} in Feed, p.p.m.	1	3	0	3
		After one Week of Operation		
Item				
1. Aerator Suspended Solids, g.	2.26	2.13	3.16	2.83
2. P^{32} in Sludge, dpm in millions	4.87	3.41	2.1	2.54
3. P^{32} in Sludge, μc	2.2	1.54	0.95	1.15
4. P^{32}, μc/gram Sludge Solids	0.97	0.72	0.3	0.4
5. P^{32}, μc/kilo. of 3 per cent Sludge	29.2	21.6	9.0	12.0
		After Two Weeks of Operation		
1. Aerator Suspended Solids, g.	2.29	1.80	2.54	2.79
2. P^{32} in Sludge, dpm in millions	8.4	3.96	3.35	3.00
3. P^{32} in Sludge, μc.	3.78	1.78	1.51	1.35
4. P^{32}, μc/gram Sludge Solids	1.65	0.99	0.60	0.48
5. P^{32}, μc/kilo. of 3% Activated Sludge	48.5	29.7	17.8	14.5

TABLE 7

Summary of I^{131} Operating Data

Activated Sludge No.	Synthetic Sewage Feed* E	Synthetic Sewage Feed* F	Sewage Feed** G	Sewage Feed** H
B.O.D. Load, lbs/1000 c.f./day	44	44	33	33
P^{31} added, p.p.m.	2.0-2.5	2.0-2.5	-	-
I^{127} added, p.p.m.	1.0	3.0	1.0	3.0
I^{131} added, dpm/ml.	1,370	1,370	1,370	1,370
Aerator Susp. Solids, p.p.m.	4000-6300	3400-4800	1300-2000	2000-2900
Volume of Sludge (1) ml./liter	140-220	160-270	40-90	50-105
I^{131} in Mixed Liquor, dpm/ml.	2140-2500	1710-2240	1410-1840	1480-2130
I^{131} in Supernatant, dpm/ml.	1,350	1,340	1,230	1,230
Removal of I^{131} by Act. Sludge, per cent	1.4	2.7	10.3	10.0

(*) Feed of .375 grams of flour and .125 grams of dextrose given twice a day.
(**) Feed at 800 ml. of sewage twice a day.
(1) Milliliters of sludge after 30 minutes settling.

TABLE 8

The Relative Amounts of Major Radioactive Elements in Fission Product after 3 Months*

Element	Atomic No.	Half-life s = seconds d = days y = years	Relative Abundance Per cent
Strontium	89	53 d	9.9
Strontium-Yttrium	90	25 y	1.5
Yttrium	91	57 d	13.0
Zirconium	95	65 d	15.4
Niobium	95	35 d	25.1
Ruthenium	103	42 d	7.2
Ruthenium	106	365 d	1.2
Rhodium (daughter)	106	30 s	1.2
Cesium	137	33 y	0.7
Cerium	141	28 d	4.9
Cerium	144	275 d	15.7
Promethium	147	3.7 y	2.9
			Total 98.7

(*) Calculated from Tompkins, Khyn and Cohn [15] data.

TABLE 9

The Absorption of Mixed Fission Product by Activated Sludge

Aeration Time Hours	SLUDGE A RADIOACTIVITY (1,960 p.p.m. Susp. Solids)			SLUDGE B RADIOACTIVITY (1,820 p.p.m. Susp. Solids)		
	Added dpm/ml.	In Super. dpm/ml.	Absorbed per cent	Added dpm/ml.	In Super. dpm/ml.	Absorbed per cent
0	945			4,700		
0.02					2,225	50
0.33		650	31			
1		535	43			
3		270	71			
4		220	77		1,125	75
24		120	87			

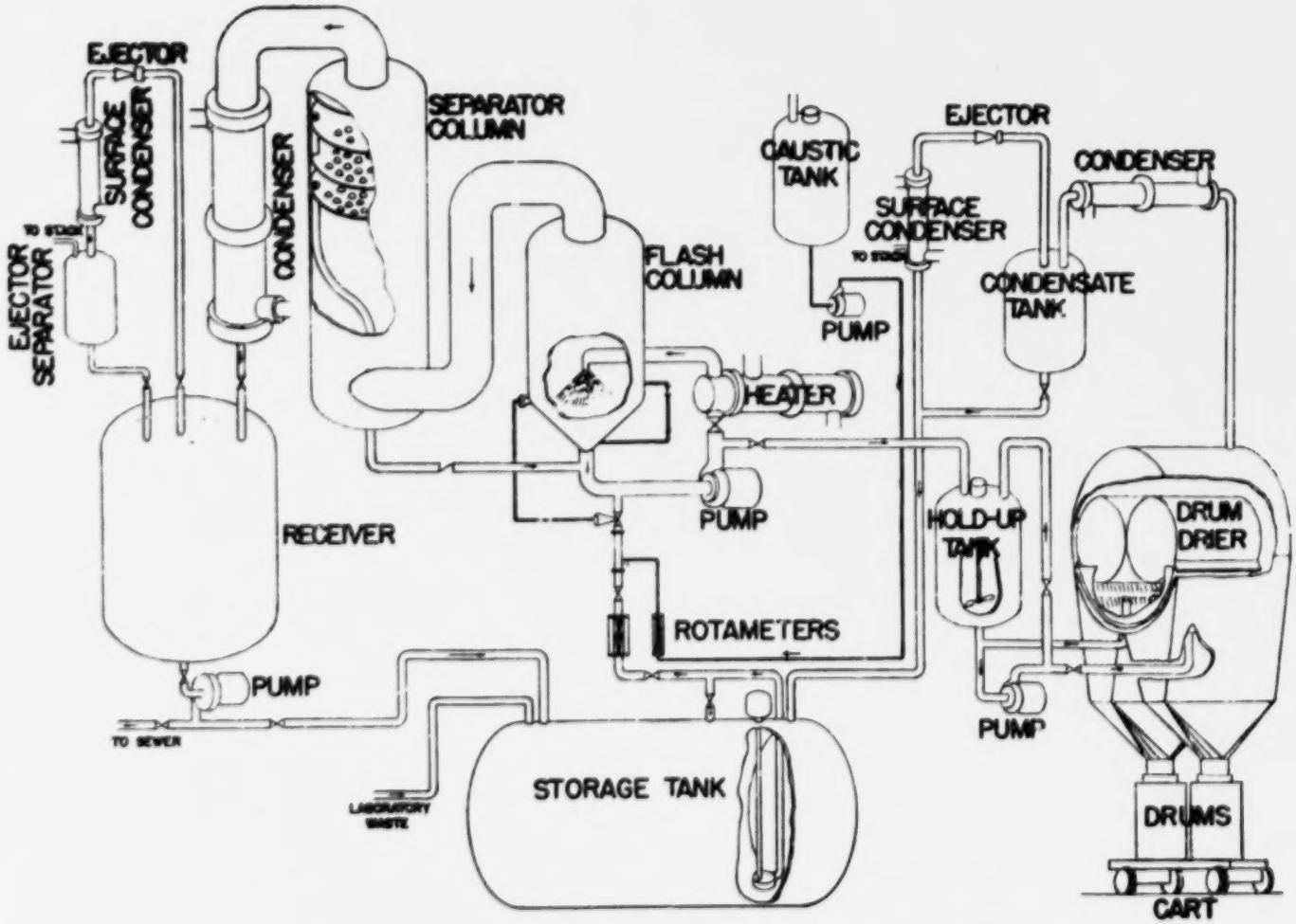
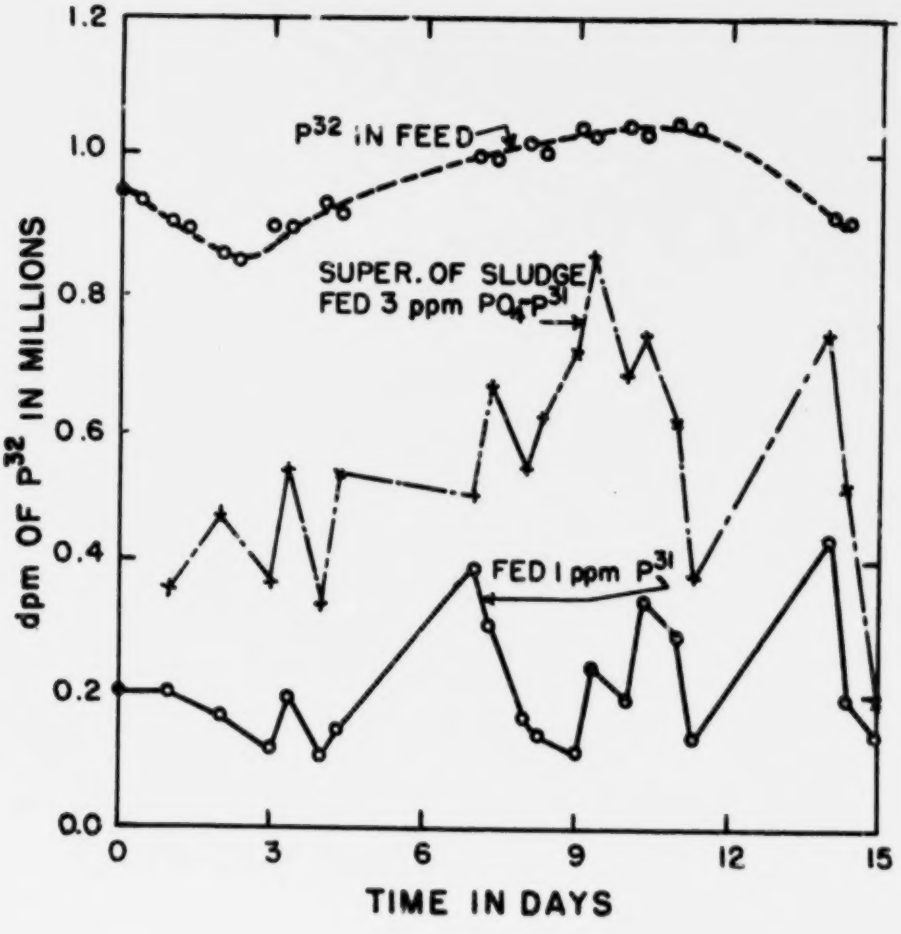


FIGURE 1 FLOW DIAGRAM.

Figure 2

Fluctuations in the radioactivity (P^{32}) of supernatants from activated sludge fed synthetic sewage (flour-dextrose) fortified with stable phosphate (P^{31}).

P^{32} in feed = 855,000 to 1,040,000 or an average of 960,000 dpm in an aerator volume of 1 liter.


1.2
1.0
0.8
0.6
0.4
0.2
0.0
dpm OF P32 IN MILLIONS
P32 IN FEED
SUPER. OF SLUDGE
FED 3 ppm PO4P31
FED 1 ppm P31
0
3
6
9
12
15
TIME IN DAYS

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